

The nature and observability of protogalaxies

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Abstract. I discuss recent theoretical work on the formation and evolution of galaxies paying particular attention to the ability of current models to make detailed comparisons with observations of the galaxy population both nearby and at high redshift. These models suggest that much (perhaps most) star formation in the universe took place in objects that are already detected in deep galaxy samples. In addition, they predict that systems with large star formation rates are unlikely to be much more abundant in the past than they are at present. Recent data show that the star formation rate in the nearby universe is, in fact, a substantial fraction of that required to make all the stars seen in galaxies, and that the observed abundance of objects forming stars at rates in excess of $10M_{\odot}/\text{yr}$ is approximately the same at redshifts of 1.25 and 3.25 as it is at $z = 0$. Both the epoch of galaxy formation and “typical” protogalaxies may already have been observed but not recognised. Thermal emission from dust in such protogalaxies could be detected by a large millimeter array, and molecular line observations could explore the dynamical state of the gas in the more massive systems.

1 Introduction

The traditional approach to interpreting observational data on the faint galaxy population is grounded firmly in the work which Beatrice Tinsley carried out in the 1970’s (see Tinsley 1980). One starts from a characterisation of the local galaxy population in terms of the abundance of objects as a function of luminosity and Hubble type. One assumes that star formation always occurs with an Initial Mass Function (IMF) similar to that inferred from observations of the disk population in the Solar Neighborhood. One picks a simple parameterized model for the star-formation history of a galaxy specified, for example, by the redshift at which star formation starts, the fraction of the stars form in an initial burst, and the characteristic timescale with which formation of the remaining stars decays exponentially in time. These parameters are then adjusted separately for each Hubble type so that the synthesised stellar population at redshift zero has colours which agree with those observed for nearby galaxies. These simple models then allow one to predict the luminosity and colour which a present day galaxy would have if it were seen, for example, at $z = 1$.

This simple scheme can make full use of the information we have about nearby galaxies and of our knowledge of stellar evolution. In addition, it is easily extended to include, for example, a separate treatment of the bulges and disks of spiral galaxies, or a phenomenological treatment of starbursts. It allows one to use the counts, colours and redshift distributions of faint galaxies, to look for possible constraints on cosmological parameters and on the “epoch of

galaxy formation". Furthermore, the assumption of a well defined collapse epoch when a burst forms a significant fraction of the final stellar population has been traditional since the earliest discussions of galaxy formation (e.g. Partridge and Peebles 1967) and has virtue of predicting that the collapsing protogalaxy should be very bright and so, perhaps, easily observable. The failure to find such objects has convinced many observers that galaxy formation must occur at high redshift. An interesting variant of the traditional approach is presented by Gronwall and Koo (1995) who show that it can still explain much of the recent data.

With the refurbishment of the HST and the advent of spectroscopy on 10 meter telescopes, this kind of approach is no longer adequate. Samples of field galaxies can now be studied to redshift 3 and beyond, and the new morphological and spectral data show that these objects cannot simply be considered as present-day galaxies whose star-formation is at a less advanced stage but whose structure is otherwise unaltered. The distant objects are often disturbed, are in most cases relatively small, and typically show evidence for substantial ongoing star formation (Cowie et al 1995; Steidel et al 1996; Giavalisco et al 1996, Abraham et al 1996). It seems likely that an understanding of their relation to nearby systems will only be obtained through more detailed consideration of how different types of galaxies were assembled and made their stars.

Theoretical understanding of the formation and evolution of galaxies has improved greatly over the past two decades. Surveys of the spatial and kinematic distributions of galaxies, together with simulations which demonstrate how gravity can produce these distributions, have led to a much clearer picture of the likely context for galaxy formation than was available in the 1970's. This picture can be further explored at high redshift using quasar absorption lines (e.g. Cen et al 1994; Katz et al 1996). In addition, studies of the stellar populations within galaxies and of interacting galaxies have highlighted the role of galaxy transformation processes like starbursts and mergers. As I now discuss, hierarchical clustering theory can be used to build a phenomenology of galaxy formation which is physically based, relatively simple, tuned to agree with detailed simulation results where these are available, and designed to allow direct comparison with observation.

2 The current structure formation paradigm

A well-developed "standard" picture for the formation of structure has been adopted as a working hypothesis by most cosmologists. Its main elements are the following.

- Most of the matter in the universe is in some dark, nonbaryonic form. It must be dark because all attempts to observe radiation from the dominant component in galaxy clusters or in the outer halos of galaxies have failed. It must be nonbaryonic because the mass content of the universe inferred from dynamical and gravitational lensing measurements exceeds the baryonic content required if the observed abundances of light elements is to be consistent with the theory of Big Bang nucleosynthesis.

- Baryonic matter is present in the amount predicted by Big Bang nucleosynthesis. This is few percent of the closure density, and is significantly larger than the amount observed directly in the form of stars or intergalactic gas.
- Deviations from uniformity were small in the early universe and were generated at very early times, probably by quantum effects during inflation. This process imposed no characteristic scale relevant to the formation of galaxies or larger structures, and produced a gaussian field of linear density fluctuations. An alternative, structure generation at late times by topological defects such as cosmic strings or textures, has attracted less attention because its consequences are much harder to calculate.
- Structure grows through gravitational instability. Radiation pressure on the gas and dispersive motions in the dark matter can have significant effects at early times, but later evolution is driven entirely by the gravity of the dark matter until the collapse of the dark halos of galaxies.
- Galaxies form at late times by the dissipative settling of gas to the centres of the potential wells provided by dark matter halos. This explains the observed segregation between luminous and dark matter in galaxies as well as the origin of the spin of galactic disks.

At cosmology conferences this framework is usually taken for granted; arguments tend to centre on the parameter values which define specific implementations of it (H_0 , Ω , Ω_b , Λ , dark matter type, etc.). For non-specialists, however, it can seem more relevant to question whether the universe really is made primarily of some entirely new form of matter, and whether all the structure we see really arose from quantum zero-point fluctuations when the universe was $\sim 10^{-35}$ s old. As a scheme for forming galaxies and larger structures, this hierarchical picture was outlined by White and Rees (1978) and has been developed in recent years both by numerical simulations (e.g. Katz et al 1992; Navarro et al 1995) and by detailed semi-analytic treatments of the relevant physical processes.

3 Hierarchical galaxy formation

The formation of galaxies is expected to occur in a very similar way in most currently popular versions of the paradigm just discussed. (These are usually designated by acronyms, for example, SCDM, CHDM, τ CDM, OCDM, Λ CDM, TCDM, PIB, texture+HDM; I will not here discuss the relative merits of these possibilities.) The dominant processes shaping the evolution of the galaxy population and the structure and morphology of galaxies are the following.

- The dark matter clusters hierarchically from a gaussian field of initial density fluctuations. Small objects form first and merge together to make larger ones. A well-developed analytic theory for the dynamics and statistics of this process and also for the structure of the resulting objects has been tested in considerable detail against numerical simulations (Lacey & Cole 1993, 1994; Cole & Lacey 1996; Mo & White 1996; Navarro et al 1996).

- Gas cools and collects at the centres of dark halos to form cold rotationally supported disks. As first shown by Fall and Efstathiou (1980), the observed angular momenta of spiral galaxy disks can be produced by tidal torques at early times *only* if the disks formed within an extended massive halo in this way.
- Star formation occurs: (a) in quiescent disks; (b) in bursts during galaxy collisions and mergers; (c) during the initial collapse of a galaxy/halo system. In the present universe most star formation occurs in mode (a), but mode (b) is also significant. In a hierarchical model there is little distinction between collapse and merging, and so between modes (b) and (c).
- Winds from massive stars and shocks from supernovae may reheat cold gas in galaxy disks and may affect the accretion of new gas from the surrounding halo. Such feedback effects appear necessary to limit the efficiency of star formation and to ensure that sufficient gas remains at late times to form the large galaxies which contain most observed stars. Direct evidence for strong feedback associated with vigorous star formation is seen in the “superwinds” generated by some starburst galaxies (Heckman et al 1990).
- Ellipticals form by the merger of disk/bulge systems made primarily of stars. Gas may condense to form a new disk around such an elliptical and so transform it back into the bulge of a spiral. The first process is observed directly in the nearby universe, although there is controversy over the fraction of ellipticals produced by it. Direct evidence for the second can, perhaps, be found in the discovery of a nearby spiral with a counter-rotating bulge (Prada et al 1996).
- When dark halos merge the galaxies within them remain distinct. Thus a massive “cluster” dark halo can contain many galaxies, and the halo of a spiral galaxy may include a number of small satellites. Galaxy mergers occur when dynamical friction brings the orbit of a subsidiary galaxy near the centre of its dark halo where it can encounter the dominant galaxy which resides there. Thus the Milky Way will accrete the Magellanic Clouds, and the cD galaxies at cluster centres can grow by swallowing other cluster galaxies as well as by accreting more gas from surrounding cooling flows.

All of the above processes seem certain to play a role in shaping the observed galaxy population. The difficulty lies in specifying when they should occur and what their relative importance should be. In addition one needs methods to calculate their effect. The analytic description of hierarchical clustering referred to above can be extended to generate Monte Carlo realisations of the full merging history of a present-day dark halo (Kauffmann & White 1993). Within such a merger tree it is possible use simplified analytic descriptions of the relevant physical processes to follow the formation, evolution and interaction of all the galaxies which end up in the final halo. By considering many halos with the appropriate mass distribution, it is then possible to reconstruct the galaxy population in a representative region of the universe.

This programme was first carried out by Kauffmann et al (1993) who showed that if parameters are tuned so that a dark halo with circular velocity of 220

km/s typically contains a system resembling the Milky Way, then hierarchical models reproduce many of the observed regularities of the local galaxy population. For example, the Tully-Fisher relation, the bulge-to-disk ratios of spirals, the morphology-environment and gas fraction-environment relations, the colour-morphology relation, the rich cluster luminosity function and luminosity-morphology relation, all these are well reproduced. The most serious discrepancy affects the field galaxy luminosity function which has the correct number of bright galaxies but too many faint ones. Models which come close to fitting the nearby galaxy population can also be consistent (with no further adjustment) with the available counts and redshift distributions for faint galaxies (Kauffmann et al 1994). An independent implementation of this programme by Cole et al (1994) differs substantially in many details but comes to similar conclusions. In Heyl et al (1995) these authors also studied how the success of such schemes depends on the particular cosmology in which they are implemented.

Such attempts to build physically based models differ fundamentally from the traditional Tinsley approach. Both schemes use population synthesis models to predict the photometric properties of galaxies, but the resemblance stops there. The traditional approach treats each galaxy independently of all others. The galaxy population at high redshift can be identified one-to-one with the nearby population whose properties are adopted from observation rather than derived from a model. The epoch of galaxy formation is a parameter of the arbitrary analytic form chosen to describe star formation histories, and is adjusted to fit faint galaxy data. In contrast, galaxies form and transform continually in the hierarchical models. There is no simple relationship between the galaxies at $z = 1$ and those at $z = 0$. Some old ellipticals have grown new disks, some old spirals have merged to make new ellipticals, and a significant amount of the matter in nearby galaxies was in *no* galaxy at $z = 1$. The parameters which are adjusted describe the efficiencies of uncertain physical processes (for example, star formation, feedback and dynamical friction) and only indirectly influence the formation history of galaxies. The present properties of the galaxy population are not built in *a priori*, but are predictions of the model; as a result they usually show some discrepancies with observation.

The advantage of the hierarchical models is that because they offer a complete, albeit schematic, description of the history of the galaxy population, they can be used to address a very broad range of questions. For example, with Monte Carlo realisations of the full formation history of cluster galaxies one can study the conditions necessary for an observable Butcher-Oemler effect, for the elliptical colour-luminosity relation to be as tight as observed, and for this relation to evolve as observed. One can also check whether the star formation histories of “field” ellipticals (and thus their colours) are expected to differ systematically from those of cluster ellipticals. These questions were addressed by Kauffmann (1995, 1996) who found that the observed strength of the Butcher-Oemler effect appears to require a high density universe, that such a universe can be consistent with the tight colour-luminosity relation of cluster ellipticals, and that field ellipticals are predicted to be younger (and so bluer) than cluster ellipticals.

Figure 1 shows the average formation history predicted for elliptical galaxies in rich clusters for a CDM universe with $\Omega = 1$ and $H_0 = 50$ km/s/Mpc. About 55% of the stars in the ellipticals formed more than 10 Gyr ago and almost none less than 4 Gyrs ago. On the other hand, the typical elliptical had its last major merger about 7 Gyrs ago, so that most of the stars were formed well before the observed galaxies were assembled. From this figure we can infer that the stars in, say, a $10^{11}M_\odot$ elliptical galaxy were forming rapidly around 11 Gyr ago, corresponding to $z = 2.5$. At this time the star formation rate was of order $0.2 \times 10^{11}M_\odot/1\text{Gyr} = 20M_\odot/\text{yr}$. However, the galaxy was in several pieces, so the star formation rate in the largest piece was $\sim 10M_\odot/\text{yr}$. This is an order of magnitude smaller than the rate inferred in traditional models where a bright elliptical forms in a single burst of duration 1 Gyr or less.

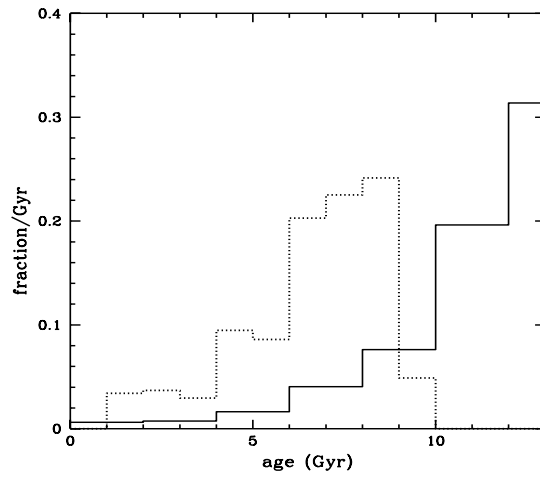


Fig.1. The solid histogram is the stellar age distribution for elliptical galaxies in rich galaxy clusters according to a standard CDM model with $\Omega = 1$ and $H_0 = 50$ km/s/Mpc. The dotted histogram gives the time of the last major merger for this same population of galaxies. For field ellipticals both histograms would be shifted to lower ages. For field galaxies in general the stellar age distribution becomes much flatter. (Adapted from fig. 3 of Kauffmann 1996).

Hierarchical models automatically specify luminosities and morphologies for all galaxies at all redshifts, and so it is easy to predict galaxy counts as a function of morphology as well as of colour and apparent magnitude. In the Hubble Deep Field galaxies can be classified to much fainter limits than was previously possible. Baugh et al (1996) show that the counts presented by Abraham et al (1996) are in good agreement with their previously published hierarchical models – the rapidly rising count of irregular and star-forming systems is

reproduced quite naturally. The models also predict redshift distributions as a function of morphology, and it should soon be possible to test these predictions directly. Hierarchical models can also predict the spatial distribution of galaxies as a function of luminosity and type. A first analysis has been presented by Kauffmann et al (1996) who show that the observed difference in clustering between spirals and ellipticals and between bright galaxies and dwarfs is easily reproduced. However, in the rest of this contribution I concentrate on the star formation history of the galaxy population since it is this which relates most directly to millimeter observations. The case of cluster ellipticals, discussed above, illustrates the major point; star formation occurs at lower redshifts, in smaller objects, and at lower rates than in traditional models.

4 The abundance of star-forming galaxies

The best observational measure of the star-formation rate in nearby galaxies is generally thought to be $H\alpha$ luminosity. A recent survey by Gallego et al (1995) has determined the first reliable luminosity function for the local universe based purely on $H\alpha$ selection. These authors find that the galaxies which provide most of the nearby star-formation differ from those which dominate the optical luminosity density. The star-forming galaxies are typically late-type systems with luminosities well below L_* and with star formation occurring predominantly in a compact nuclear region. The $H\alpha$ luminosities can be converted to star-formation rates assuming a standard solar neighborhood IMF, and the data then give the local abundance of galaxies as a function of star-formation rate. This distribution is shown in cumulative form in Figure 2. By integrating over all luminosities Gallego et al estimate a total star-formation rate of $0.013 M_\odot/\text{yr}/\text{Mpc}^3$ where here and below $H_0 = 50 \text{ km/s/Mpc}$.

It is interesting to compare this number with the total mass density of stars in the local universe. The APM redshift sample of Loveday et al (1992) covers the largest volume surveyed to date and leads to an estimated luminosity density of $6.5 \times 10^7 L_\odot/\text{Mpc}^3$ in the B band. According to Efstathiou et al (1988) 40% of the B light comes from E/S0 galaxies and the rest from spirals. The detailed kinematic study of van der Marel (1991) shows that the mean M/L of early type galaxies is 3.2 in B after averaging over an appropriate luminosity function. For spirals Persic and Salucci (1992) estimate $M/L_B \approx 1.0$ after subtracting the contribution of dark halos to the estimated dynamical masses. Putting all these numbers together gives a total star density of $1.2 \times 10^8 M_\odot/\text{Mpc}^3$. Thus the local star formation rate observed by Gallego et al appears enough to make all the stars observed by Loveday et al in about 10 Gyrs. The overall star formation rate need never have been higher in the past than it is today.

In fact there is mounting evidence that the luminosity density inferred from the APM sample is too low by about a factor of 2, perhaps because of photometric problems (Ellis et al 1996; Bertin & Dennefeld 1996). In this case the average past star formation rate would need to be twice the currently observed value. This seems consistent with the detection of strongly enhanced star formation in

intrinsically *faint* galaxies at redshifts beyond 0.3 (Ellis et al 1996; Lilly et al 1995). However, these same samples show little evidence for an enhancement of the abundance of rapidly star-forming systems, and in fact, as I now show, there appears to be no such enhancement out to redshifts beyond 3.

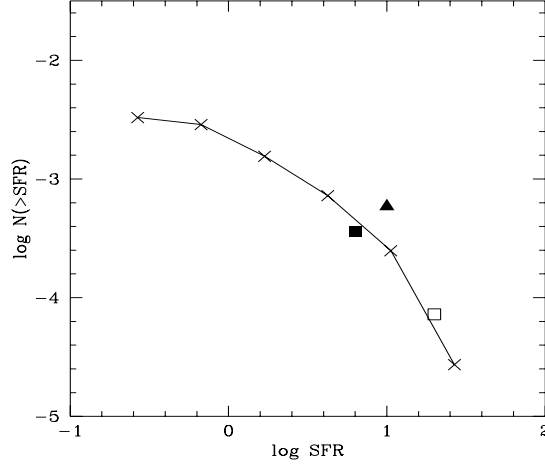


Fig. 2. The crosses linked by a solid line show the abundance (in Mpc^{-3}) of nearby galaxies with star-formation rates exceeding a given value (in $\text{M}_{\odot}/\text{yr}$) plotted against that value. The data are taken from Gallego et al (1995). The triangle is the abundance estimated at $z \sim 1.25$ from the data of Cowie et al (1995) while the squares are similar estimates at $z \sim 3.25$ from the data of Steidel et al (1996). Filled symbols assume $q_0 = 0.5$ while the open square assumes $q_0 = 0.05$.

Cowie et al (1995) present redshift and emission line data for an almost complete sample of galaxies with $B < 24.5$. Both population modelling of the UV continuum and the emission line data in their figure 3 suggest that their sample should be complete for objects with unobscured star-formation rates greater than $10 \text{ M}_{\odot}/\text{yr}$ over the redshift range $1.0 < z < 1.5$. They find an average of 0.7 such objects per square arcmin, leading to a mean comoving abundance of $6.4 \times 10^{-4} \text{Mpc}^{-3}$ assuming $q_0 = 0.5$. The same exercise can also be carried out at higher redshift. Steidel et al (1996) argue that their Lyman limit imaging technique finds all galaxies in the redshift range $3 < z < 3.5$ with $R > 25$. This band corresponds to the far UV continuum in the galaxy rest frame, and they estimate $R > 25$ to correspond to an unobscured star-formation rate exceeding $6.3 \text{ M}_{\odot}/\text{yr}$. They find 0.4 such objects per square arcmin giving a comoving volume density of $3.6 \times 10^{-4} \text{Mpc}^{-3}$. I plot both abundances on top of the local data in figure 2. Remarkably, the abundance of systems forming stars faster than $10 \text{ M}_{\odot}/\text{yr}$ is similar at $z = 3.25$, at $z = 1.25$ and at $z = 0$. If one

instead adopts $q_0 = 0.05$ the star-formation rate for the Steidel et al galaxies increases by a factor of 3 but their abundance drops by a factor of 5. As figure 2 shows the inferred abundance is still similar to that seen locally.

It thus appears that although global star-formation rates were higher in the past, the enhancement resulted purely from an increase in the number of systems forming stars at modest rates. A new population of unobscured massive starbursts is not seen at redshifts less than 3.5. It should, however, be noted that the star-formation rates are estimated in different ways for each of the three samples in figure 2; hence systematic shifts in the relative calibration might change the impression given by this plot.

5 Millimeter observations of young galaxies

In hierarchical models most star formation occurs relatively late. (The equivalent of Figure 1 but for all the stars in the universe shows a much more gentle decline to the present.) In addition there is no period when bulges and ellipticals form rapidly as single units and so are very bright. Instead star formation in the past occurred in lower mass and more gas-rich objects than today but at rates comparable to those in nearby systems. It seems unlikely that extreme objects like the superluminous IRAS starburst sources were ever much more abundant than they are today. The observational data in figure 2 support this conclusion but it is important to note that they refer to unobscured star-formation. Most of the radiation in the strongest nearby starbursts is absorbed by dust and reradiated in the far infrared. In addition, the fraction of the energy emitted by dust seems to be greater in systems which are more dynamically disturbed. Both observational and theoretical arguments suggest that a larger fraction of star-forming objects are irregular at high redshift, so the fraction of the energy radiated in the FIR may be much greater than it is locally.

The amount of heated molecular gas and the amount of hot dust are the key parameters which determine the observability of distant galaxies by a millimeter array. A further important parameter is the size of the emitting region. Recent studies of distant galaxies find that the UV-emitting regions are almost always small with typical angular sizes well below one arcsec, corresponding to physical sizes of a kiloparsec or two. The physically-based models I have discussed make significantly more pessimistic predictions than *ad hoc* models which typically extrapolate the strong evolution detected in nearby samples of IRAS galaxies in order to predict the FIR emission at $1 < z < 5$ (e.g. Rowan-Robinson, this volume). Objects with star-formation rates of $30 \text{ M}_\odot/\text{yr}$ are found in both the Cowie et al and Steidel et al samples. Since these surveys covered very small areas it is likely that objects will be found forming stars at $100 \text{ M}_\odot/\text{yr}$ over the full redshift range $z < 4$; at least some of these objects may emit most of their radiation in the FIR and would then be only a few times less luminous than nearby ultraluminous IR galaxies (e.g. Clements et al 1996). Scaling from such systems shows that an order of magnitude increase in sensitivity of millimeter interferometers would allow line observations of young galaxies at $z > 1$ and

detections of the dust emission from the most luminous systems at high redshift ($z = 4$ to 5). The detection of millimeter lines will be particularly important because it will give information about the dynamical state of the gas during the early stages of galaxy assembly. An angular resolution approaching 0.1 arcsec will be needed to map the emitting gas in most systems.

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